APOD Mission Status and Observations by VLBI

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Abstract On September 20, 2015, 20 satellites were successfully launched from the TaiYuan Satellite Launch Center by a Chinese CZ-6 test rocket and are, since then, operated in a circular, near-polar orbit at an altitude of 520 km. Among these satellites, a set of four CubSats, named APOD (Atmospheric density detection and Precise Orbit Determination), are intended for atmospheric density in-situ detection and derivation via precise orbit. The APOD satellites, manufactured by DFH Co., carry a number of instruments including a density detector, a dual-frequency GNSS (GPS/BD) receiver, an SLR reflector, and a VLBI S/X beacon. The APOD mission aims at detecting the atmospheric density below 520 km. The ground segment is controlled by BACC (Beijing Aerospace Control Center) including payload operation as well as science data receiving, processing, archiving, and distribution. Currently, the in-orbit test of the nano-satellites and their payloads are completed, and preliminary results show that the precision of the orbit determination is about 10 cm derived from both an overlap comparison and an SLR observation validation. The in-situ detected density calibrated by orbit-derived density demonstrates that the accuracy of atmospheric mass density is approximately 4.191×10^{-14} kgm^{-3}, about 5.5% of the measurement value. Since three space-geodetic techniques (i.e., GNSS, SLR, and VLBI) are co-located on the APOD nano-satellites, the observations can be used for combination and validation in order to detect systematic differences. Furthermore, the observations of the APOD satellites by VLBI radio telescopes can be used in an ideal fashion to link the dynamical reference frames of the satellite with the terrestrial and, most importantly, with the celestial reference frame as defined by the positions of quasars. The possibility of observing the APOD satellites by IVS VLBI radio telescopes will be analyzed, considering continental-size VLBI observing networks and the small telescopes with sufficient speed.

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Keywords APOD, atmospheric density, VLBI

1 Introduction

The precise orbit prediction of LEO spacecraft is very important for space debris collision avoidance, orbit maneuvers of LEO spacecraft, and rendezvous and docking of the space station. But it is still a huge challenge for the spacecraft operators. One of the main reasons is that the atmospheric density is known not accurately enough. At the altitude of LEO spacecraft, atmospheric density variations are driven by variations in the solar ultraviolet irradiance, electrical energetic particles from the magnetosphere, and solar wind and waves originating in the lower atmosphere that propagate upward. There are many atmosphere models describing the variations of the density, including empirical and physical models. Improving the accuracy of these models is a very challenging task and needs high-quality observations of mass density (direct or indirect) with sufficient spatial and temporal resolutions and coverage. Since the 1960's, many techniques have been developed to measure the atmospheric mass density and composition, including drag-derived means by orbit of spacecraft, in-situ measurements

Table 1 APOD payload system.

		nano-sat
Atmosphere density detector	Detection range [km]	120 $\sim$ 550
	Pressure measure range [Pa]	$1.0^{-6} \sim 1.0^{-2}$
	Temperature range [°C]	$-20 \sim 60$
	Sampling rate [s]	1
GNSS receiver	Mode	GPS/BDS
	GPS frequency [MHz]	L1: 1575.42, L2: 1227.60
	BDS frequency [MHz]	B1: 1561.098, B3: 1250.618
	Sampling rate [s]	8
Laser retro reflector	Type	Pyramid
	Number of cube corner prisms	9
VLBI beacon	S-Band frequency [MHz]	$f_{carrier}$=2262.01, $f_{S_{dor1}}$=2256.87, $f_{S_{dor2}}$=2260.98, $f_{S_{dor3}}$=2263.04, $f_{S_{dor4}}$=2267.15
	X-Band frequency [MHz]	$f_{carrier}$=8424.02, $f_{X_{dor1}}$=8404.87, $f_{X_{dor2}}$=8420.19, $f_{X_{dor3}}$=8427.85, $f_{X_{dor4}}$=8431.66

by neutral mass spectrometers, ultraviolet remote sensing and other techniques as rocket payload or ground based [1]. Especially, both CHAMP and GRACE have generated an unprecedented volume of high-quality measurements of the mass density and contributed to great achievements in atmospheric density research and modeling. Still, more extensive spatial and temporal coverage is needed to improve the accuracy of the models because of the complexity of the variations of atmosphere. The cost to meet this requirement is huge. But the development of low-cost CubSat provides a very good opportunity to detect atmospheric density with a more extensive spatial coverage. Thus BACC/AFDL (Beijing Aerospace Control Center/Aerospace Flight Dynamic Laboratory) proposed the APOD project to test the technology of in-situ detection by a payload instrument and to derive precise orbits on CubSats.

2 Satellites and Payload Overview

Inside the APOD family, there are one nano-satellite called APOD-A and three pico-satellites called APOD-B/C/D. The four satellites are flying in a circular, near-polar orbit with an inclination of about 97°. All four satellites were orbiting at an altitude of 520 km directly after launch. Then APOD-A descended to 470 km altitude two weeks later. The designed lifetime is twelve months. In order to obtain atmospheric density by the in-situ detector and from the precise orbits, the instruments used for the precise orbit determination and density detection are mounted on the APOD satellites (Figure 1). The instrumentation includes a the dual-frequency GNSS receiver, an atmospheric density detector, an SLR Reflector, and a VLBI beacon. The APOD payload is listed in Table 1; it was a great challenge to integrate these instruments in such a miniature satellite.

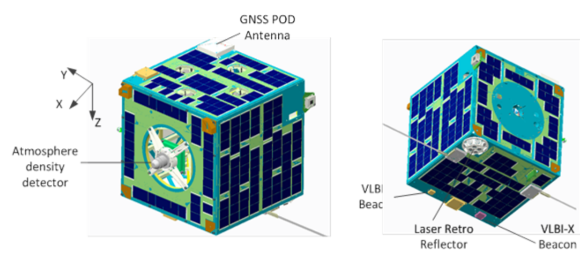

Fig. 1 Physical layout of the APOD nano-sat with the location of the scientific instruments: front side view (left) and bottom side view (right).

3 Preliminary Results

3.1 Precise Orbit Determination (POD)

Since the launch of APOD, the in-orbit commissioning of the platform and payload have been finished, and now APOD is in ordinary operation. The POD is performed by GPS L1/L2 double differences carrier phase data. The data rate is about 1/8 Hz or lower because of lost lock of carrier phase. BACC produces precise orbit products by a POD software with independent intellectual property rights. The orbit precision is verified by the XiAn Satellite Control Center (XSCC) using the Bernese software. For POD based on GNSS L1/L2, a batch processing using 30 hours with a 12-hour overlap is employed. To avoid boundary effects, we only consider ten hours of these overlaps. Figure 2 shows the standard deviation of the GNSS L1/L2 POD solution of APOD-A. Losing lock of the signal in L2 is serious, leading to negative influences on the orbit precision.

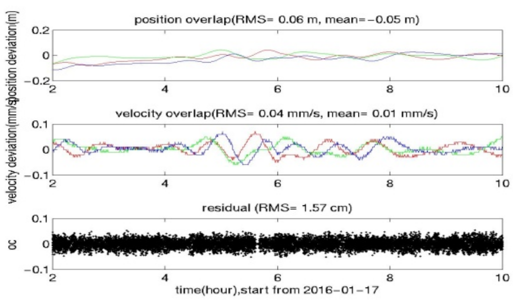

Fig. 2 Overlap comparisons of nano-sat: position (top), velocity (middle), and O–C in POD of GPS L1/L2 carrier phase (bottom).

The orbit precision has been validated independently by Satellite Laser Ranging (SLR). The International Laser Ranging Service (ILRS) provides SLR measurements to the APOD satellites. BACC is responsible for guiding the SLR stations by uploading satellite prediction files to the ILRS Web site in Consolidated Prediction Format (CPF). At the time of writing, APOD nano-sat had been tracked by 13 SLR stations all over the world. More than 4000 normal point data have been accessed since the first normal point data was obtained on 2 October 2015 by CHAL and SHA2 SLR stations. The SLR measurements are used for an independent validation of the GNSS-derived orbits. The names of the APOD satellites in the ILRS are PN-1A, PN-1B, PN-1C, and PN-1D, respectively. A detailed description of the LRR and the measurement conditions of the APOD satellites are described on ILRS Web site at (`http://ilrs.gsfc.nasa.gov/missions/satellite_missions/future_missions/pn1a_general.html`). ITRF2008 coordinates are used for the SLR stations, the CoM offset of the LRR array is corrected according to the parameters described on the ILRS Web site. The normal point data, whose residuals are larger than 30 cm and whose elevation angles are less than 15°, are removed. Figure 3 shows the differences between the SLR measured ranges and the ranges derived from the GPS L1/L2 carrier phase POD.

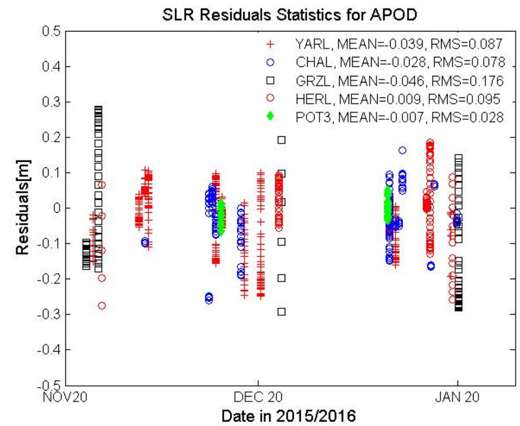

Fig. 3 SLR residuals for POD. The mean residual and standard deviation of every station are marked in the figure. Their values for all stations are −2.93 cm and 9.85 cm, respectively.

From the overlap comparison of the GNSS derived orbit and the independent validation by SLR measurement, the POD accuracy of the APOD-A satellite is at the 10-cm level, which can meet the requirement of the mission.

APOD is the first LEO satellite with a VLBI S/X beacon. The APOD orbit was also validated independently by the Chinese CEI (Connected-Element Interferometry). On March 10, 2016, a CEI constituted by a three-meter antenna and a 12-meter antenna observed the APOD satellites, where the S-band radio signals including the main-carrier, DOR beacons are tracked and recorded. The local oscillators of the recording channels are 2262 MHz, 2267.15 MHz, and 2256.85 MHz, respectively. The bandwidth is 1 MHz and the quantization digit is 8 bits, being the same for all recording channels. According to the traditional signal processing algorithm, the interferometric delay (DOR, Differential One-way Range) is completed. Following the DOR processing algorithm, the interferometric delay of the APOD satellite is obtained. Figure 4 shows the VLBI observations of the APOD nano-sat with respect to the APOD orbit.

From a VLBI observational point-of-view, the APOD satellite constitutes a challenge since the

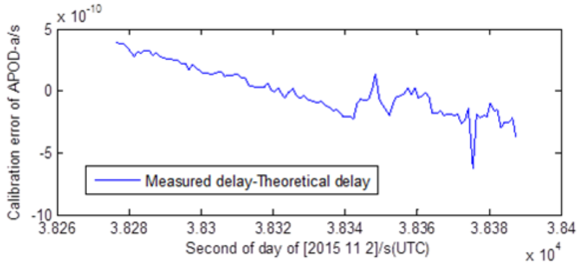

Fig. 4 O–C of VLBI observations for the APOD nano-sat.

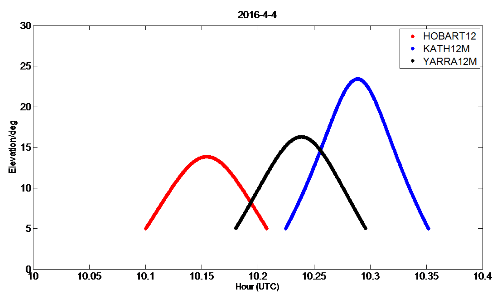

Fig. 5 Elevation plot of APOD as seen from AuScope.

mutual visibility depends on the altitude of the APOD satellite and the separation of the radio telescopes [2]. Further, the APOD satellite travels very fast through the field of view. The first VLBI observations to APOD were carried out successfully with the three AuScope VLBI observatories on April 4, 2016. The good condition to co-view APOD with AuScope can be found in Figure 5. BACC generated the schedule in VEX format using VieVS [3] in the stepwise tracking mode, i.e., each satellite observation was given as a source in (RA, Dec) coordinates with an update every 12 seconds. The maximum az/el velocity was 30°/min and 6°/min for the APOD observation, respectively. Observations to quasars were scheduled before and after the observations to the APOD satellites [4]. The VLBI data was transferred to BACC, where the correlation and processing of the APOD data was started by the VLBI team of BACC.

4 Atmospheric Density

In the APOD mission, two independent methods are designed to obtain the atmospheric mass density. One method is the drag-derived mass density and the other is in-situ Atmospheric Density Detector (hereafter ADD). Drag-derived densities from LEO satellite orbits are the most common and direct method to determine atmospheric mass density. The basic principle of this method is that the primary effect of the atmospheric drag acceleration reduces the semi-major axis of the LEO satellite monotonically. ADD, manufactured by National Space Science Center (NSSC), is a space-borne device which consists of a spherical gold-plated stainless steel antechamber with a knife-edged orifice inlet, an electron impact ion source, and electronics. Figure 6 gives a comparison between the verified in-situ atmospheric density and the drag-derived atmospheric density with respect to the NRLMSISE-00 model.

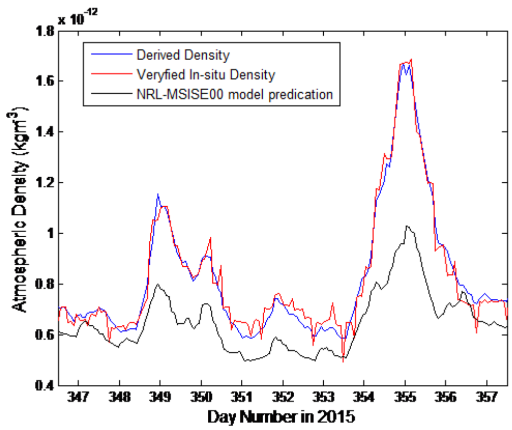

Fig. 6 Comparison between the verified in-situ atmospheric density and the orbit-derived atmospheric density.

5 Summary

The APOD project demonstrated excellent prospects for low-cost CubeSat in detecting atmospheric density in a much more extensive spatial coverage and much higher temporal resolution. The preliminary result about the orbit precision was validated independently by different methods. It shows that the three-dimensional position precision of the APOD satellite is about 10 cm. With the precise orbit, the in-situ Atmospheric Density Detector data was calibrated by orbit-derived density and the fitting precision of the detected density is approximately 4.191×10^{-14} kgm^{-3}, which is about 5.5% of the orbit-derived value. Further VLBI observations with IVS antennas would provide more possibilities to study systematic differences and to link the reference frames.

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